Discovery of an extremely red galaxy at z=0.65 with dusty star formation and nuclear activity [1]

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ABSTRACT

In the course of the follow-up multiwavelength study of a deep radio survey we have discovered that the milli-Jansky radio source PDFJ011423 is a low-redshift ($z = 0.65$) extremely red galaxy (ERG) with $K = 15.3$, $R-K = 5.8$ and $J-K = 3.1$. Optical, infrared and radio photometry, together with optical and near-infrared spectroscopy, reveal a heavily obscured galaxy (A_V=5–6, from the observed Balmer decrement) undergoing vigorous star formation and presenting an active galactic nucleus (AGN). PDFJ011423 is a representative member of the dusty ERG population, providing a local counterpart for studying more distant ERGs.

Subject headings: galaxies: individual (PDFJ011423) — galaxies: photometry — galaxies: active — galaxies: starburst — infrared: galaxies — radio continuum: galaxies

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[1]Based on observations with the *Infrared Space Observatory*, Australia Telescope Compact Array, Anglo Australian Telescope, Cerro Tololo Interamerican Observatory and the European Southern Observatory (prg: 266.A-5633)

1. INTRODUCTION

Deep multi-wavelength near-infrared and optical surveys over the last decade have led to the discovery of a population of galaxies with very red optical-infrared colors (**?**, "extremely red galaxies", hereafter ERGs; e.g.)]Els88,Mcc92,Hu94,Tho99,Dad00. ERGs, defined as galaxies with $R - K > 5$, appear to fall into two sub-classes: (1) high redshift ($z \gtrsim 1$) evolved elliptical galaxies with intrinsically red spectral energy distributions (SEDs) (**?**, e.g.)]Spi97,Sti99,Soi99 and (2) highly obscured dusty galaxies undergoing starburst activity (**?**, e.g.)]Cim98,Dey99,Sma99. The predominance in the ERG population of the latter would favor hierarchical galaxy formation scenarios (White & Frenk 1991), while the former would support early formation of galaxies through monolithic collapse (Larson 1975). Therefore, the study of ERGs can help constraining existing models for formation and evolution of galaxies.

The observed very red colors of those ERGs which are classified as elliptical galaxies are attributed predominantly to the large K-correction arising from their high redshift. On the other hand, star-forming galaxies will owe their redness predominantly to dust extinction. This view implies that extremely red ellipticals will occur only at high redshift ($z \gtrsim 1$) while extremely red galaxies at $z \lesssim 1$ will exhibit unusually heavy obscuration of either stellar or AGN emission, or both. This is expected to be the reason for the small space density found for ERGs in the local Universe.

This letter reports the discovery of an ERG, PDFJ011423, at $z = 0.65$. Multi-waveband photometric and spectroscopic observations reveal evidence of both star formation and AGN activity in this galaxy, which can be regarded as a "local" template for the study of this class of ERG at higher redshifts. Throughout this paper we adopt $H_0 = 65\ h_{65}\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $q_0 = 0.5$.

2. OBSERVATIONS

PDFJ011423 ($\alpha = 01^h14^m23^s$, $\delta = -45°34'30''$, J2000) was first noted as a faint 1.4 GHz radio source ($S_{1.4\,\mathrm{GHz}} = 1.67\,\mathrm{mJy}$) in the Phoenix Deep Survey (Hopkins *et al.* 1998, 1999). Aperture photometry of the optical counterpart of the source gives R=21.1 and V=22.7 (Georgakakis *et al.* 1999), locating PDFJ011423 close to the magnitude limit of the follow-up Two Degree Field multi-fibre spectroscopic survey (Georgakakis *et al.* 1999). Nevertheless, a strong emission line, identified as [OII]3727 at a redshift $z = 0.65$, was detected.

In the light of the known strong correlation between the far-infrared (FIR) and 1.4 GHz luminosities for star-forming galaxies, these clues were sufficient to schedule PDFJ011423

for observation by the *Infrared Space Observatory* (*ISO*), using ISOCAM (7 and 15 μm) and ISOPHOT (90 μm). The *ISO* observations (J. Afonso *et al.*, in preparation) revealed the presence of a relatively bright source at 7 and 15 μm, with fluxes of 4.1 and 7.6 mJy, respectively. The object was also detected by *ISO* at 90 μm (4σ level), with a flux of 260 mJy. Subsequent near-IR photometry, using the New Technology Telescope (NTT) and the CTIO 1.5m telescopes, showed this galaxy to have K=15.3 and J=18.4. PDFJ011423 is thus classified as an ERG with $R - K = 5.8$ and $J - K = 3.1$.

The closeness and the relatively bright optical luminosity of PDFJ011423 allows detailed spectroscopy of this object at both optical and near-IR wavelengths. The optical spectroscopic observations were obtained at the Very Large Telescope (VLT) using the FORS1 instrument in longslit mode. Three dithered observations of 15 minutes each were made using a 1.6″ wide slit and a low resolution grism (150I+17), covering the wavelength range $\lambda\lambda$0.6–1.1 μm. Bias subtraction, flatfielding and the combination of the dithered observations were performed before extracting the final spectrum using the software package IRAF. The wavelength scale was defined by fitting a third order polynomial to the lines of a He-Ar calibration spectrum. The spectrum of the standard star GD50 was taken for the flux calibration, which agrees with the optical photometry of PDFJ011423 within 15%. Near-infrared spectroscopy was obtained using SOFI on the ESO New Technology Telescope. Twelve observations of 270 seconds each, dithered along a 1.0″ slit, were obtained. The low resolution grism covering the range $\lambda\lambda$0.95–1.64 μm was used. The dithered observations were flatfielded and combined before the spectrum was extracted. For the wavelength calibration a Xe lamp spectrum was used. The photometric calibration was performed using the J-band magnitude of the galaxy. The final calibrated spectra are presented in Figure 1 with the respective line measurements, based on Gaussian fits to the emission lines, given in Table 1.

3. NATURE OF PDFJ011423

We approach the interpretation of the observed spectral energy distribution (SED) of PDFJ011423 (Figure 2) by attempting first to model its continuum emission, and then checking for consistency with the observed spectral line emission. The SED of a normal *elliptical* galaxy can only reproduce the observed very red colors of PDFJ011423 at $z \gtrsim 1$. This contradiction with the known redshift, combined with the presence of strong emission lines, eliminates PDFJ011423 as an elliptical galaxy.

The high luminosity of the galaxy at rest-frame 60 μm suggests the presence of a dusty starburst, while not excluding the possibility that some of the near-IR and mid-IR luminosity arises from nuclear activity. Accordingly, we have matched the observed fluxes by com-

bining the model SEDs of a starburst occurring in evolving, dusty giant molecular clouds (GMCs) (Efstathiou, Rowan-Robinson & Siebenmorgen 2000) and of a dust-enshrouded AGN (Rowan-Robinson 1995). Although it is possible that the two energising phenomena are physically linked (**?**, e.g.)]Row95, here we simply superimpose the SEDs predicted by the two models.

The model fit, presented in Figure 2, results from a χ^2 minimization to the observed SED, varying within the domain of the parameters of the original starburst and AGN models. The more powerful component, responsible for 76% of the infrared luminosity ($L_{1-1000\,\mu m}$), is a model of a dusty starburst of age 57 Myr, with optical opacities of the GMCs in the range $\tau_{\rm v} = 3 - 200$. The properties of this component are determined primarily by the constraints imposed by the FIR and optical emission.

The starburst component alone is, however, unable to fit the mid-IR data. Therefore, an extra contribution in the form of emission from hot dust ($\rm T \sim 160 - 1600\,K$) heated by a putative AGN is required. This component represents 24% of the total infrared luminosity. Acceptable fits could also be obtained using other AGN models, for example by allowing for emission from a dusty torus surrounding the central (black hole) source (Efstathiou, Hough & Young 1995). Both classes of models lead to similar descriptions of the object in the context of this paper.

The best fitted model SED in Figure 2 predicts an infrared luminosity of $\rm L_{1-1000\,\mu m} = 7.1{\times}10^{12}\ h_{65}^{-2}\,L_{\odot}$, which classifies PDFJ011423 as an ultra-luminous infrared galaxy (ULIRG). The possibility that the high luminosity is due to gravitational lensing is unlikely, given the relatively low redshift of the object.

The existence of only one data point in the FIR/sub-mm part of the SED makes an estimate of the dust mass for PDFJ011423 highly uncertain. However, the fitted SED in this wavelength range is compatible with an optically thin thermal dust emission spectrum (emissivity index of 1.5) with a temperature of $\rm T_{dust} = 33 \pm 3\,K$, which corresponds to a dust mass of $\rm M_{\mathit{dust}} \sim 8 - 30 \times\ 10^8\ h_{65}^{-2}\,M_{\odot}$ (Hildebrand 1983). Consistent with the extreme reddening of the galaxy, this value is an order of magnitude higher than the dust mass of $10^7 - 10^8\ h_{65}^{-2}\,\rm M_{\odot}$ found for local ULIRGs (Sanders & Mirabel 1996) and comparable to the higher values found in the sample of PG quasars of Haas *et al.* (2000), for example.

The two models used to fit the observed SED do not predict the radio continuum luminosity or spectral index. To interpret the radio data, we appeal to the remarkably tight empirical correlation between the FIR and radio continuum luminosity observed in star-forming galaxies (Helou, Soifer & Rowan-Robinson 1985; Condon 1972). The favored explanation of the correlation holds that the same massive stars warm the FIR-emitting

dust and energise, through supernova explosions, the relativistic electrons responsible for the radio continuum. Given the FIR luminosity of PDFJ011423, this correlation predicts a 1.4 GHz flux in the range 1.3 – 3.3 mJy compared with the measured value of 1.67 mJy. This agreement supports the possibility that most of the radio emission comes from star formation processes. It should however be noted that a similar radio/FIR correlation holds for samples of radio-quiet quasars, perhaps as a consequence of links between star formation and black hole feeding rates. The relatively flat radio spectral index observed here, $\alpha_{1.4}^{2.4} = 0.16$ ($S_\nu \propto \nu^{-\alpha}$), while being frequently linked to quasar emission (**?**, e.g.)]Web95, has also been observed in compact starburst nuclei of ULIRGs (Sopp & Alexander 1991; Crawford *et al.* 1996). The available radio images do not have sufficient spatial resolution to reveal any structure in PDFJ011423 and cannot aid to clarify the origin of the radio emission.

We now consider the spectral properties of PDFJ011423, using optical and near-IR line diagnostics from Figure 1. Since the Hα+[NII] blend is not resolved by the NIR spectrum, we assume the Hα/[NII] ratio to have a value between 1 (**?**, typical of Seyfert galaxies, e.g.)]Vei87 and 2 (**?**, corresponding to star-forming galaxies,)]Ken92 in order to separate the two contributions. With the de-blended Hα line intensity, the observed Balmer line ratio becomes Hα/H$\beta = 15 - 20$. Assuming Case B Balmer recombination (adopting the intrinsic value for Hα/Hβ as 2.85 for star-forming galaxies (Brocklehurst 1971) and 3.1 for narrow line AGNs (Veilleux & Osterbrock 1987)) and a standard Galactic extinction curve (**?**)using $R_V = 3.1$]Car89, we estimate an optical dust extinction of $A_V = 5 - 6$ mag. This large extinction is likely to be the source of the extreme red color in PDFJ011423. The absence of the 4000 Å break in the optical spectrum, indicating an optical continuum dominated by very young stars, is consistent with the inference that this is a vigorously star-forming galaxy. The measured optical line widths are not significantly larger than the instrumental resolution, placing an upper limit of approximately 500 km s^{-1} on their intrinsic value. In the NIR spectrum, the Hα+[NII] blend presents a width value of (FWHM) ~ 2000 km s^{-1} (after correction for instrumental resolution). Given the low resolution of the spectrum it is not clear if this shows an intrinsic broad line component for Hα or is due to significant contribution from [NII].

The diagnostic line ratios (Rola, Terlevich & Terlevich 1997; Veilleux & Osterbrock 1987) for PDFJ011423, after correction for dust obscuration, are consistent with the two component model. While ratios involving the [OII]3727 line ([OII]3727/H$\beta = 8.0$), indicate excitation by an AGN, the other line ratios ([OIII]5007/Hβ=2.9, [SII]/Hα=0.2–0.3) and the non-detection of [OI]6300 are indicative of a starburst. This kind of ambiguous spectral line classification has been linked previously to galaxies composite in nature, i.e., hosting both a starburst and an AGN (Hill *et al.* 1999).

The presence of an AGN in addition to the starburst component complicates the estimation of the star formation rate (SFR). The most reliable measure is from its 60 μm luminosity ($2.4 \times\ 10^{26}\ h_{65}^{-2}\,\mathrm{W\,Hz^{-1}}$) where the model implies that the dominant contribution is due to the starburst. Using the appropriate calibration (Cram *et al.* 1998) for an initial mass function (IMF) of the form $\Psi(\mathrm{M}) \sim \mathrm{M}^{-2.5}$ with stellar masses between 0.1 and 100 $\mathrm{M}_\odot$, we estimate a SFR for massive stars of $\mathrm{SFR}_{60\,\mu\mathrm{m}}$ ($\mathrm{M} \geq 5\,\mathrm{M}_\odot$)= 470 h_{65}^{-2} $\mathrm{M}_\odot$ yr^{-1}. Alternatively, from the observed radio power ($\mathrm{P}_{1.4\,\mathrm{GHz}} = 1.5 \times\ 10^{24}\ h_{65}^{-2}\,\mathrm{W\,Hz^{-1}}$) we deduce $\mathrm{SFR}_{1.4\,\mathrm{GHz}}$ ($\mathrm{M} \geq 5\,\mathrm{M}_\odot$)= 377 h_{65}^{-2} $\mathrm{M}_\odot$ yr^{-1}, consistent with the value estimated from the 60 μm luminosity. On the other hand, the extinction-corrected Hα luminosity ($\mathrm{L}_{\mathrm{H}\alpha} = 0.9-2.6\times10^{37}\ h_{65}^{-2}$ W) implies $\mathrm{SFR}_{\mathrm{H}\alpha}(\mathrm{M} \geq 5\,\mathrm{M}_\odot) = 620 - 1730\ h_{65}^{-2}$ $\mathrm{M}_\odot$ yr^{-1}, the large range being due to the unresolved contribution of [NII] to the observed Hα+[NII] blend. This excess over the SFR estimated from FIR and radio luminosities may be due to the AGN contribution.

Three other dusty ERGs have been spectroscopically confirmed and are relatively well studied: HR10, displaying strong starburst activity at $z = 1.44$ (Dey *et al.* 1999); ISOJ1324-2016, a $z = 1.50$ galaxy which hosts a dusty quasar (Pierre *et al.* 2001) and EROJ164023, which at $z = 1.05$ shows star-forming activity with a possible weak AGN (Smith *et al.* 2001). A brief comparison of some of the observed quantities in PDFJ011423 and these three other dusty ERGs is listed in Table 2. Although the non detection of star formation in ISOJ1324-2016 can be due to the lack of FIR/sub-mm observations, it seems clear that different degrees of AGN and starburst activity do exist in the dusty ERG population. Given the lower redshift of PDFJ011423, this source offers the best opportunity to study the interplay between the two phenomena in the dusty environments of these galaxies.

The ratio of the radio power to the dust-corrected optical luminosity of PDFJ011423, $P_{1.4}/L_R \sim 1$, confirms that PDFJ011423 is radio quiet. It seems likely that this source is linked to the radio-quiet counterparts of the red quasar population discovered by Webster *et al.* (1995) and also to the ERGs recently discovered among the population responsible for the hard X-ray background (Hasinger *et al.* 2001). Future work will show if the intense star formation activity present in PDFJ011423 is also a common feature to the above mentioned obscured AGN populations.

All these different studies suggest the existence of an important population of dusty ERGs, powered by heavily obscured starbursts and/or AGNs, which is now starting to be observed. Given their extreme nature, the study of the dusty ERGs will hold fundamental clues to the understanding of galaxy evolution, by revealing valuable information on the hidden star formation and AGN activity in the universe.

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Table 1. Line measurements for PDFJ011423

Line	$\lambda_{\rm obs}$ (Å)	$F_{\rm obs}$ (10^{-16} erg s^{-1} cm^{-2})	$W_{\lambda,\rm rest}$ (Å)
[OII]$\lambda\lambda$3726,3729	6159 ± 1	8.0 ± 0.3	90 ± 6
Hβ	8033 ± 4	1.0 ± 0.2	10 ± 4
[OIII]λ4959	8195 ± 4	2.0 ± 0.8	19 ± 11
[OIII]λ5007	8274 ± 4	3.7 ± 0.7	32 ± 10
Hα+[NII][a]	10858 ± 11	28.7 ± 2.5	217 ± 47

[a]Measurements from a single Gaussian fit to the observed blend.

Table 2. Comparison between the observed properties of dusty ERGs

	PDFJ011423	HR10[1]	ISOJ1324-2016[2]	EROJ164023 [3]
z	0.65	1.44	1.50	1.05
K mag	15.3	18.4	17.5	17.6
$R-K$	5.8	···	>5.2	5.9
$I-K$	···	7.8	4.9	4.5
$J-K$	3.1	2.6	···	2.1
$L_{H\alpha}$ (W)	$2.0-2.6\times10^{35}$	2.6×10^{35}	···	0.7×10^{35}
$L_{H\alpha,corr}$ (W)†	$0.9-2.6\times10^{37}$	···	···	···
$L_{10\,\mu m-2\,cm}$ ($L_{\odot}$)	6.5×10^{12}	4.0×10^{12}	···	$\lesssim 2\times10^{12}$
SFR ($M>5M_{\odot}$, $M_{\odot}\,yr^{-1}$)	~ 470	$200-400$	···	$\sim 6-400$
M_{dust} ($M_{\odot}$)	$8-30\times10^{8}$	$\sim 4\times10^{8}$	···	···
A_V (mag)	$5-6$	$2-4.5$	$4-7$	~ 5

†Hα luminosity corrected for dust extinction.

Note. — All the values are given for the cosmology adopted in this paper.

References. — (1) Dey *et al.* 1999; (2) Pierre *et al.* 2001; (3) Smith *et al.* 2001

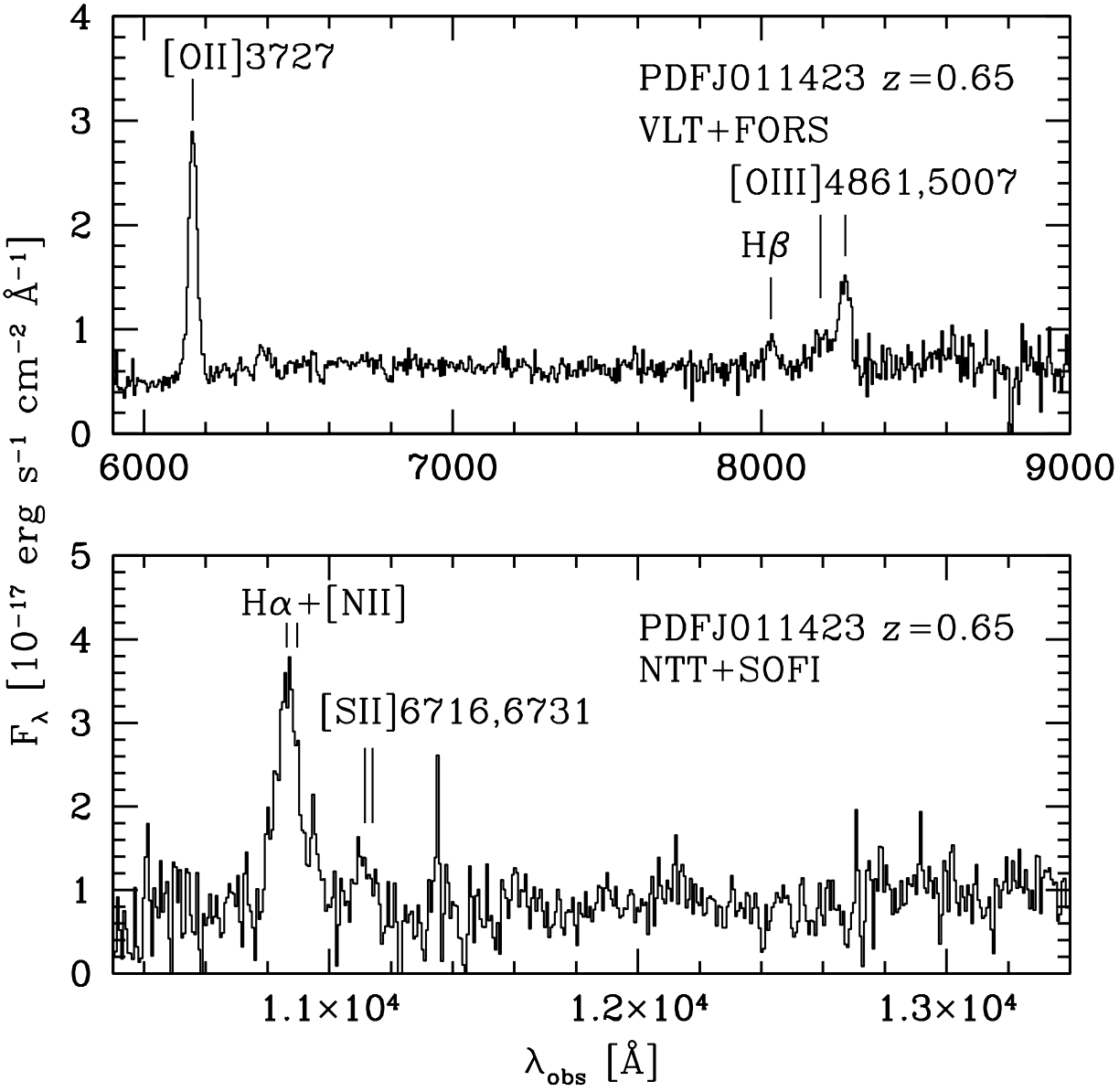

Fig. 1.— Optical and near-infrared spectra of PDFJ011423 at $z = 0.65$. The optical spectrum was obtained at the Very Large Telescope (VLT) using FORS1 while the near-infrared spectrum was obtained at the New Technology Telescope (NTT) using SOFI.

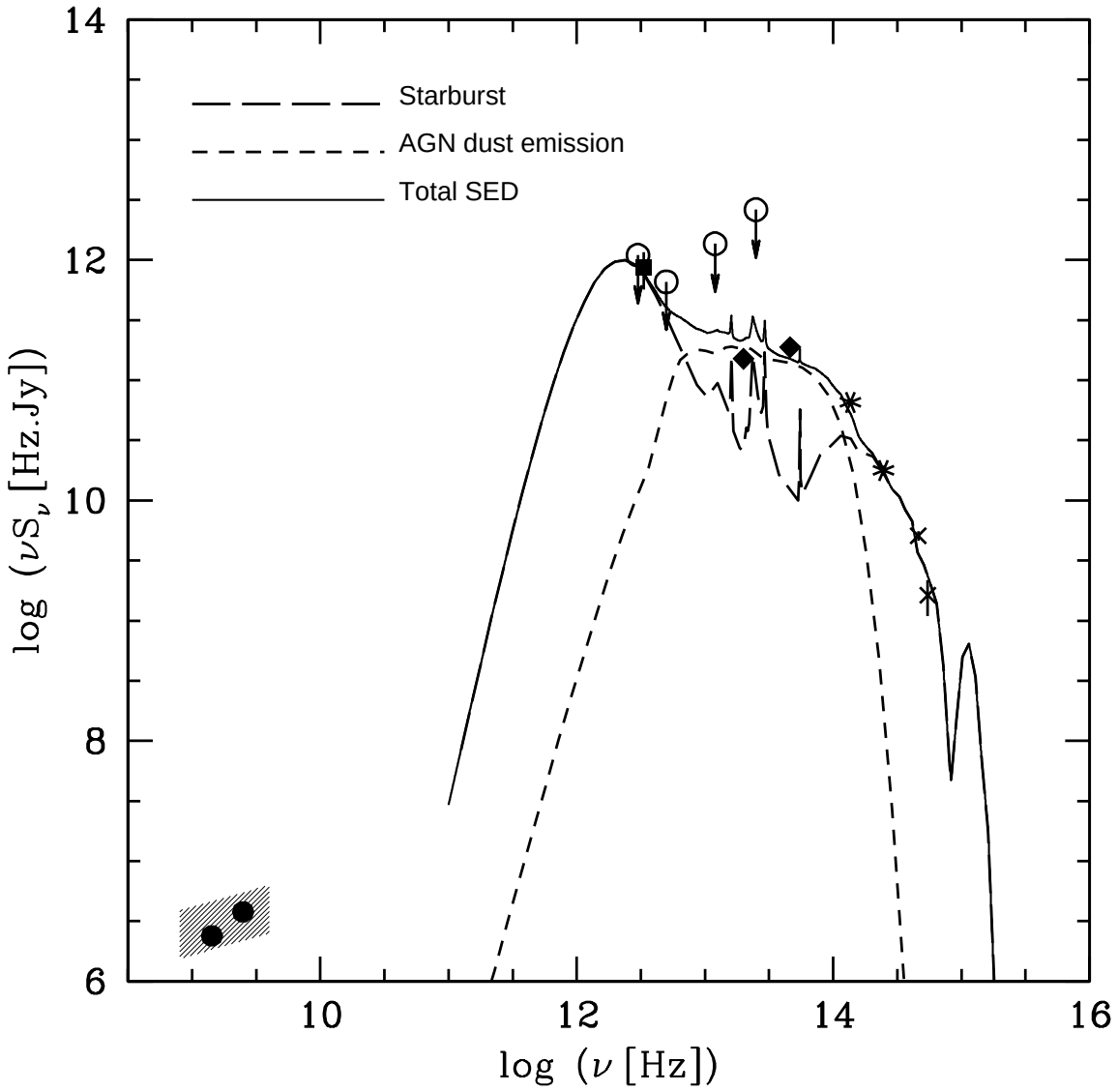

Fig. 2.— Observed SED of PDFJ011423 compared with the fitted starburst (long-dashed line) and AGN dust emission (short-dashed line) models. Crosses and stars denote, respectively, the optical (V and R-bands) and near-infrared (J and K-bands) measurements. Detections at mid and far-infrared are from ISO (filled diamonds and square) while upper limits (3σ, open circles) are shown for co-added observations from the *Infrared Astronomical Satellite* (IRAS) at λ_{obs} = 100, 60, 25, and 12 μm, estimated using the SCANPI procedure at the Infrared Processing and Analysis Center. Filled circles are the radio detections at 1.4 and 2.4 GHz. The shaded region represents the prediction of the radio flux based on FIR/radio correlation described in the text.